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Atmospheric Profiles, Clouds, and the Evolution of Sea Ice Cover in the Beaufort and Chukchi Seas: Atmospheric Observations and Modeling as Part of the Seasonal Ice Zone Reconnaissance Surveys

Dale Lawrence, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO, 80309, phone: (303) 492-3025, fax: (303) 492-7881, e-mail: dale.lawrence@colorado.edu
James Maslanik, Department of Aerospace Engineering, University of Colorado
Axel Schweiger, Applied Physics Laboratory, University of Washington,
Ron Lindsay, Applied Physics Laboratory, University of Washington
Jinlun Zhang, Applied Physics Laboratory, University of Washington
Zheng Liu, Applied Physics Laboratory, University of Washington

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LONG-TERM GOALS

The goal of this project is to examine the role of sea-ice and atmospheric interactions in the retreat of the SIZ. As sea ice retreats further, changes in lower atmospheric temperature, humidity, winds, and clouds are likely to result from changed sea ice concentrations and ocean temperatures. These changes in turn will affect the evolution of the SIZ. An appropriate representation of this feedback loop in models is critical if we want to advance prediction skill in the SIZ. To do so, we will conduct a combination of targeted measurements and modeling experiments as part of the atmospheric component of the Seasonal Ice Zone Reconnaissance Survey project (SIZRS). Combined with oceanographic and sea ice components of the SIZRS project, this project provides a multi-year observational and modeling framework that will advance our understanding of the variability of the seasonal ice zone and which is needed to improve predictions from daily to climate time scales.

OBJECTIVES

- Assess the ability of global atmospheric reanalyses and forecast models to reflect the details of the seasonal evolution of atmosphere-ice-ocean interactions in the Beaufort Sea SIZ through the use coordinated multi-year atmospheric, ice, ocean measurements,
- investigate how regional meso-scale models can improve the representation of atmosphere-ice interactions in the SIZ spring through fall,
- determine how changes in sea ice and sea surface conditions in the SIZ affect changes in cloud properties and cover,
- develop novel instrumentation including low cost, expendable, air-deployed micro-aircraft to obtain temperature and humidity profiles and cloud top and base heights
- Integrate atmospheric, oceanographic, and sea ice measurements and models to advance our understanding of seasonal ice zone variability.

APPROACH

To achieve these long-term objectives we are conducting observation and model experiments. The SIZRS project is an integrated observation and modeling program aimed at understanding the interplay of atmosphere, ice, and ocean in the SIZ of the Beaufort and Chukchi seas (BCSIZ). Seasonally changing surface conditions are expected to provide a present day analog for expected future ice retreat. SIZRS takes advantage of routine Coast Guard C-130 domain awareness missions that take place at bi-weekly intervals from May through November. As the atmospheric observation component of SIZRS, this project deploys dropsondes during SIZRS flights planned at least monthly from June through October to obtain atmospheric profiles of temperature, humidity, and winds from the time of ice edge retreat in spring to advance in fall. Transects following 150W and 140W from 72N to 77N are typically obtained. Cloud top heights will be retrieved using infrared imagers and a LIDAR provided by other SIZRS projects. In addition, we are contributing to technology development by adapting and deploying a new generation of truly expendable (<$700) micro-aerial vehicles (Glidersonde, SmartSonde) designed to obtain detailed high-vertical-resolution temperature, humidity and wind profiles and cloud layering information that cannot be obtained with traditional dropsondes.. In addition a dropsonde (IR dropsonde) capable of detecting cloud tops and bases is being developed. Satellite data from MODIS, CloudSat-Calipso as well as high resolution passive microwave and visible band optical images are utilized. Ship-based observations (Radiosonde and Cloud Ceilometer) are coordinated with SIZRS. Land based station data from the Department of Energy Atmospheric Radiation Program (ARM) are utilized to validate instrumentation. Sea surface temperatures, ice concentrations, and floe size distributions are measured by other components of the SIZRS project. Our atmospheric observations are being examined in the context of varying surface and weather conditions (sea ice concentration, ice thickness, and SST, synoptic type) to increase our understanding of atmosphere-ice-ocean interactions and to initialize, validate, and improve our meso-scale atmospheric model. Forecast experiments to assess our current ability to forecast sea ice variability at different time scales are conducted.

WORK COMPLETED

Observations:

- We adapted a commercial GPS-based radiosonde system to operate in a dropsonde mode that can be launched from aircraft. This provides an inexpensive alternative to a very limited choice in commercial suppliers of dropsonde systems.
- We completed the Aircraft Configuration Control Board (ACCB) process including safety of flight test (SOFT) and obtained approval for deploying dropsondes during ADA flights.
- We conducted successful deployments of dropsondes during 21 flights fom June –2013 – September 2015, with a total of ca. 120 profiles collected.
- We compared satellite retrievals of cloud fraction and cloud top height with observer estimates from C-130 cockpit.
- We helped advance the dropsonde design with the commercial vendor. Initial deployments were made using a converted radiosonde which now has been transitioned into a dropsonde design that is suitable for tube launches. We helped develop a simple parachute system that achieves 5 m/sec descent rates and yield high-resolution vertical profiles.
- We utilized IR-camera images obtained through the C-130 ramp during launches to obtain cloud top temperatures. Use of CUPLIS-X system (PI, Mark Tschudi, University of Colorado) with IR

and LIDAR instrumentation to provide cloud top information was recently approved for flight (First flight originally planned for Oct-6, 2015 was cancelled due to aircraft problems).

- We optimized our dropsonde launch procedure to increase the horizontal density of dropsondes.
- We conducted comparisons of dropsondes and radiosondes launched from ship by a separately funded ONR project (Overland).

Modeling:

- A post-doctoral research associate, Zheng Liu, was hired to conduct WRF model experiments.
- We conducted Weather Research and Forecast (WRF) model simulations for the summer of 2014 and compared with the NCEP Global Forecast System (GFS) and ERA-Interim reanalysis data. The results are consistent with our previous study of the 2013 simulations (Liu et al., 2015). .
- We constructed a *k*-mean clustering synoptic classification algorithm using ERA-Interim reanalysis data to investigate the role of synoptic conditions on the vertical structure of atmosphere, cloud, and their interactions with sea ice.
- We applied the synoptic classification algorithm to determine the synoptic conditions of the SIZRS flights and studied the relationship between synoptic conditions and the observed atmospheric profiles
- We conducted forecast experiments with the Marginal Ice Zone Modeling and Assimilation System (MIZMAS) and assessed the quality of sea ice drift forecasts from 6 hours to 9 days. We examined the role of wind forcing.

Advanced Observation Platforms (IR Dropsonde, GliderSonde, SmartSonde):

- Work on a SmartSonde development to obtain detailed atmospheric parameters and cloud top and base and can be launched from C-130 is progressing. In order to accelerate approval we modified the initial design from a motorized SmartSonde to a GliderSonde concept. We conducted SOFT tests for "GliderSonde" systems. ACCB approval is reportedly imminent. More details are reported herein.
- In collaboration with the vendor (MeteoModem) we modified the standard dropsonde platform to host an additional set of IR flux sensors to result in an IR dropsonde. These sensors are designed to provide cloud top and base heights, as well as detection of intermediate layers. We validated the methodology using a balloon launched sensor package in Colorado and have conducted several field deployments with overflights of ice-breaker-based and land-based ceilometers. Initial results indicate a good agreement of cloud top and base heights with ceilometer data, and with temperature and humidity profiles also measured on the sonde. Details are reported below.
- In addition to the IR flux sensor development, we tested the potential of small, inexpensive lidar and infrared ranging sensors to serve as cloud top and base sensors. The tests suggest that the inexpensive (approximately $100.00) could provide an additional cloud base/height detection approach for small UAS.

RESULTS

Results reported here focus on the IR flux and ranging sensors, IR Dropsonde and GliderSonde portions of the work, led by the University of Colorado (CU) in this collaborative project.

IR Cloud Margin Sensor

A custom IR sensor was developed at CU, consisting of an upward looking thermopile "eye" and a downward looking thermopile "eye", each producing a small voltage that is proportional to the IR flux it sees in a 90 conical field of view, with sensitivity in the 5-15 micron wavelength range. Each thermopile voltage is differenced and amplified to a 3 volt scale so that it can be converted to digital form and sent over a telemetry channel. Each sensor costs approximately $30, and is small and lightweight (see Figure 1), enabling it to be used in a variety of vehicles for carrying it to and deploying it in remote locations. The IR dropsonde incorporates this sensor into a modified commercial dropsonde (Figure 2) that can be deployed from a manned aircraft (such as the Coast Guard C-130 during periodic Arctic Domain Awareness flights). The GliderSonde incorporates this IR sensor into a gliding unmanned aerial vehicle (UAV) that can also be dropped from a manned aircraft, but then can be guided to areas of interest (e.g. seasonal ice zone margins) and can descend more slowly than a dropsonde. The SmartSonde is a GliderSonde with an electric motor and propeller that further expands the duration, vertical and lateral sampling capabilities.

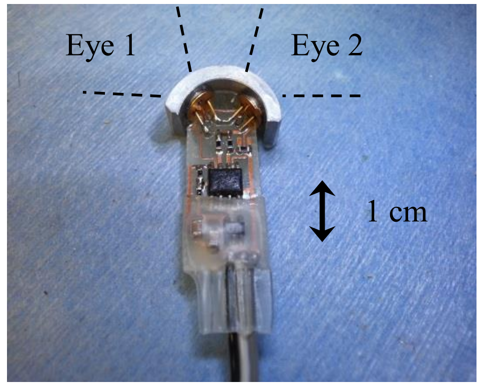


Figure 1: IR flux sensor developed at CU for in-situ cloud margin sensing.

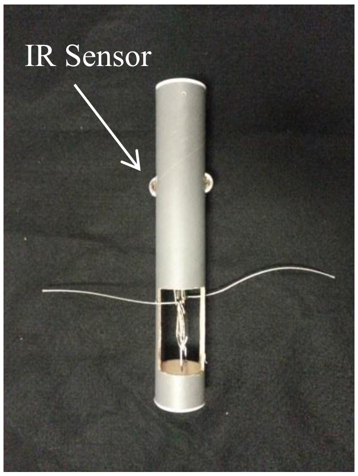


Figure 2: IR flux sensor integrated into a commercial Meteomodem drop sonde

IR Dropsonde

During a September 29, 2014 SIZRS mission we had the opportunity to overfly the Canadian Coast Guard Ice Breaker *Louis S. St-Laurent* . The ship was equipped with a laser ceilometer and radiosonde launch facility. We coordinated an overflight with simultaneous dropsonde and radiosonde launches to allow for independent validation of the dropsonde data. The overflight of a cloud ceilometer allowed a first test of the IR-dropsonde in the Arctic. (Previous validation utilized tethered balloon vehicle for the IR sensor, above a ceilometer in Boulder, CO). A comparison of ship-based ceilometer data and IR dropsonde data is shown in Figure 3. The IR dropsonde clearly identifies the two cloud layers apparent in the ceilometer data. Note that the lower layer at about 400m is very thin and diffuse, indicated by a slight increase in IR sensor signal (white/red lines), while the upper layer is much more distinct in the IR signature, first increasing due to the nearly 5 C temperature inversion (not shown) at 1800m, then decreasing abruptly with altitude as the cold, clear sky becomes visible above.

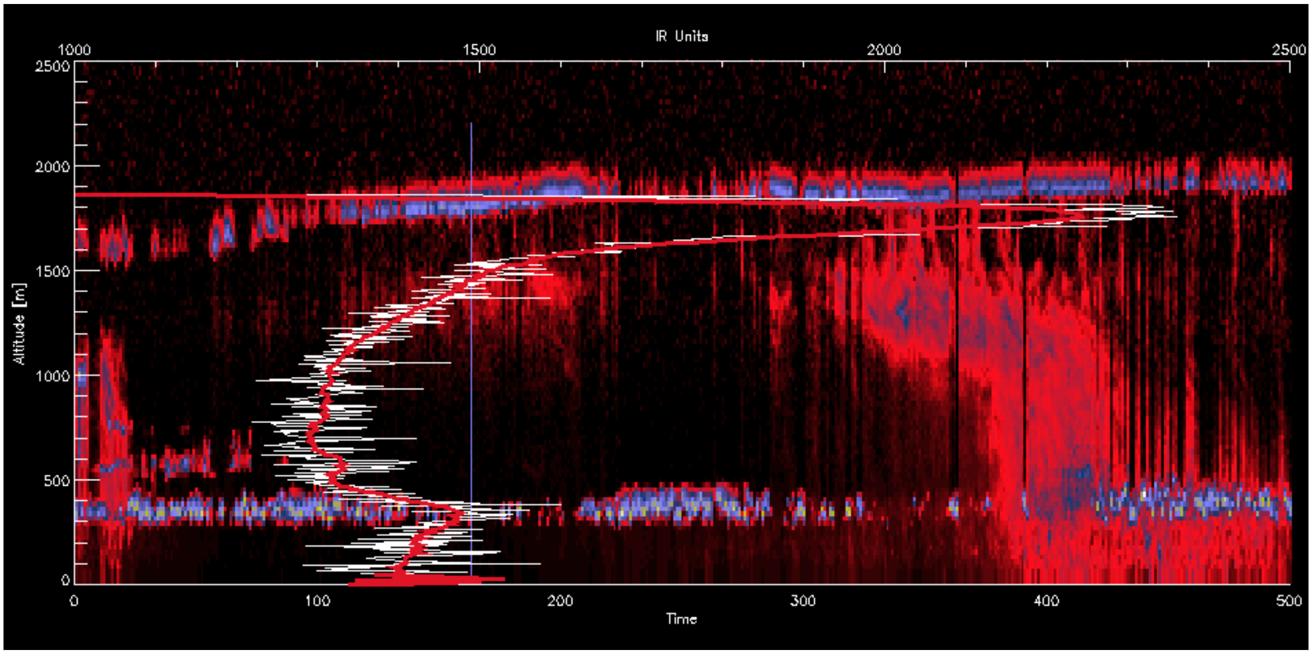


Figure 3: Time (bottom x-axis) height (y-axis) section of lidar backscatter from the ship-based ceilometer. Red to blue show backscatter values with increasing magnitude. The IR sonde profile is shown in white relative to the top x axis (IR units) with a smoothed version overplotted in red, The ceilometer backscatter data shows two distinct cloud layers which are clearly identified by the IR dropsonde.

Note that a ceilometer often cannot see beyond the lowest cloud layer when that layer is thick or dense, since too much laser energy is absorbed above. The IR flux sensor in a dropsonde, however, can detect all the cloud layers as it descends through them, providing a more complete picture of the cloud structure and the thermodynamic implications of multiple layers of varying density. Moreover, the low cost of the IR sensor enables its use on multiple sondes that can cover wider areas or reach more remote locations than land or ship-based ceilometers.

Figures 4 and 5 show the results from a more recent set of IR dropsonde profiles. The Sept. 9 2015 drop occurred over the Sandia AMF site at Oliktok Point, Alaska, and the Sept. 10 drop occurred about 670km further north over the Beaufort Sea. Each sonde was modified at CU to integrate a single IR sensor, with its analog output converted to a digital value between 0 and 4096 and inserted into the 1 Hz telemetry stream. A total of nine of the newest versions of dropsonde from Meteomodem were augmented with these IR sensors, but only two were dropped during the September 2015 SIZRS campaign. Note that the sensors installed in these newer dropsondes were oriented opposite to those in the previous campaign (Figure 3), resulting in opposite polarity of the differential flux signal (large values above the cloud top, rather than small values as before).

Both Figures 4 and 5 show IR readings near the maximum (100%) at the upper altitudes, where the sondes are above the cloud deck and the cold sky is clearly visible by the upward-looking “eye” in the sensor, and the relatively warm cloud top below is visible by the downward-looking “eye” in the sensor. The sky conditions above 1km at the more northern location (Figure 5) are clearer than over the Alaskan coast (Figure 4) where the cloud margin is more diffuse. There is a very distinct, dense cloud top at 1km altitude in the open ocean case (Figure 5), where the IR upward-downward difference abruptly decreases in value to a dense cloud value near 60% IR signal in only 50m of altitude. (The IR

signal is at 50% when both "eyes" see the same IR flux). By contrast, the near-shore profile (Figure 4) has a more gradual transition to a similar cloud density, starting at a larger altitude of 1180m over a transition zone of about 100m thick. A correspondingly strong temperature inversion is seen at this altitude. An even stronger inversion is present at 1km altitude in Figure 5, corresponding to the more abrupt change in cloud density there.

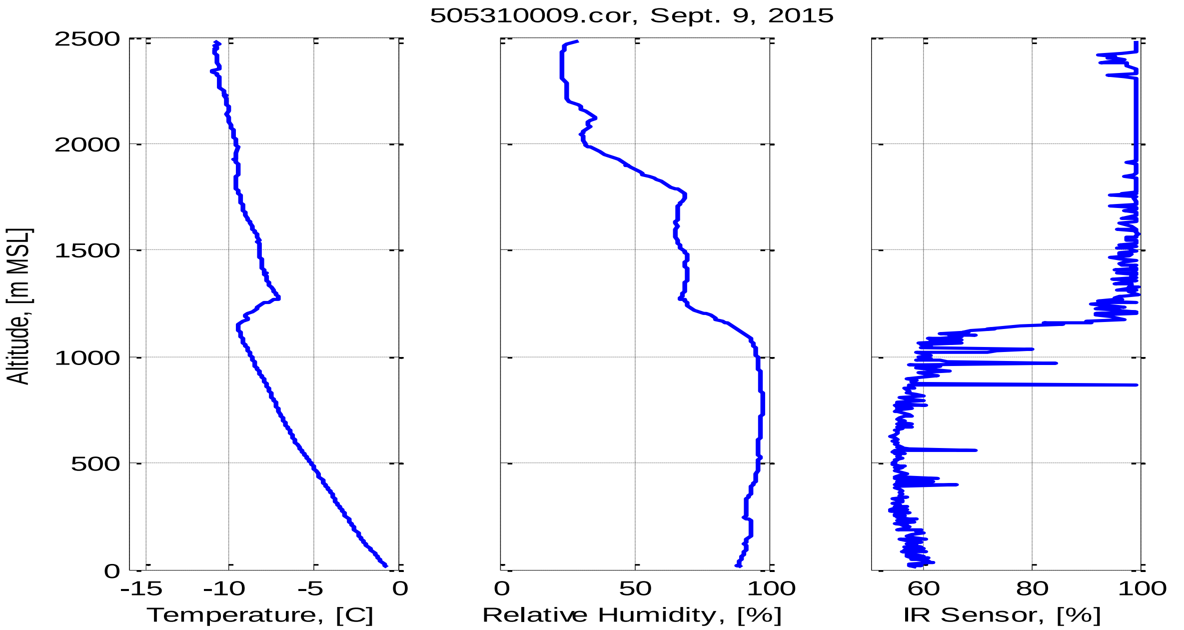


Figure 4: IR Dropsonde data for Sept. 9, 2015 at W 140 deg and N 70.6 deg, near the AMF installation at Oliktok Point, Alaska. A temperature inversion and abrupt IR cloud density change is clearly seen at 1100 to 1200m.

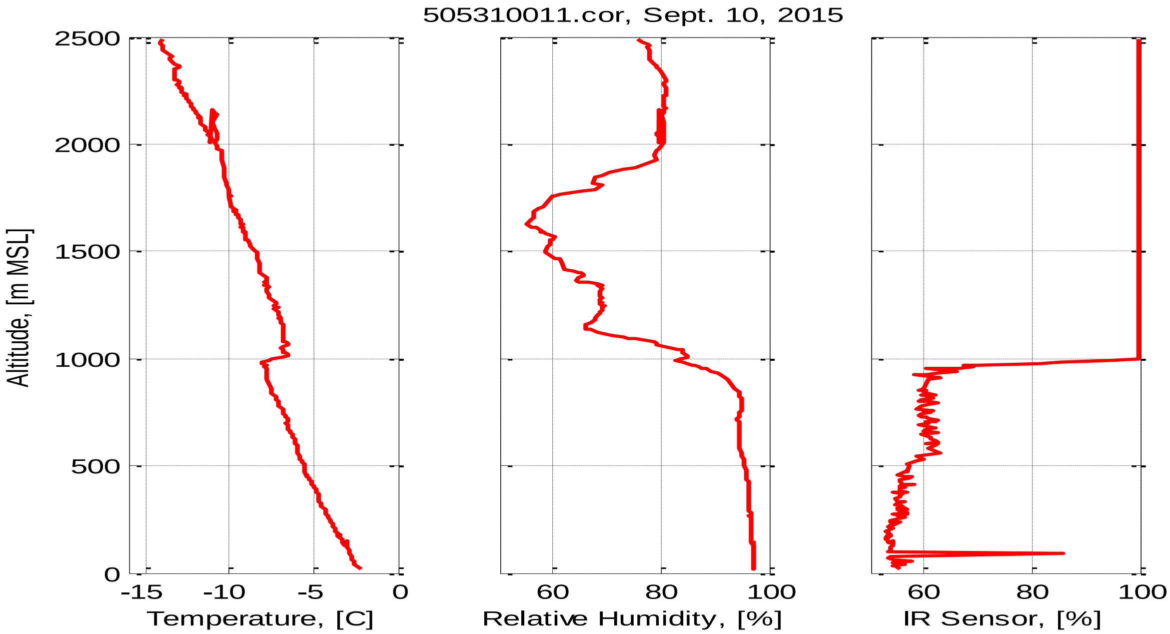


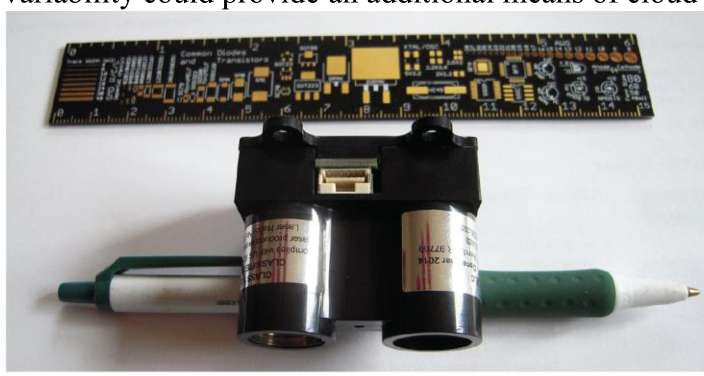
Figure 5. IR dropsonde data for Sept. 10, 2015, at W 140 deg. and N 76.6 deg. in the Beaufort Sea. An even more dramatic temperature inversion and cloud IR density change is seen in this data at 1000m.

In Figures 4 and 5, the atmosphere below the cloud top is nearly saturated, and the IR cloud density remains high all the way to the surface, hovering around the 60% sensor value. However, note that there are several strong spikes in IR signal at 1030, 970, and 870 m altitude in Figure 4, and at 90m in Figure 5. These are believed to be due to local breaks in the cloud layer, briefly exposing the sensor to more of the cold sky above. Note that the temperature and humidity signals show no sign of these inhomogeneities. Thus the IR sensor may provide additional understanding of the radiative thermodynamic conditions. This would be even more informative if the IR sensor could be guided to explore the lateral variations more thoroughly, as planned for the GliderSonde and the motorized SmartSonde.

Lidar and IR Ranging for Cloud Margin Detection

Our earlier work demonstrated that a relatively small lidar could detect the presence of mist and steam. When mounted on an aircraft, pointing either ahead or downward, such a lidar would thus provide an additional, complimentary method of mapping cloud structure. We explored this further using a newly available lidar ("LIDAR-Lite" from PulsedLight, Inc.) that is smaller (at 5cm x 4cm x 2cm and 22g) and lower cost ($115) than the previously tested version. Bench tests were carried out with the lidar alternately viewing clear sky, a target, and sky with steam and mist introduced in the view path. Results (Figure 6) suggest that the reflectance variability could provide an additional means of cloud detection. This particular lidar can also output return power and information on first and last return. Such information potentially could be used to infer additional cloud characteristics such as optical depth or cloud particle type.

Additional tests were carried out using a similar methodology applied to a Sharp, Inc. GP2Y0A710K0F infrared distance sensor, which detects range by a triangulation method rather than the lidar's time of flight approach. In this case, we tested whether mist within the view path would affect the sensor's ability to "lock on" to a target via triangulation. We found that even relatively heavy mist between the sensor and target did not noticeably affect the range measurements, suggesting little utility for cloud detection in this case.



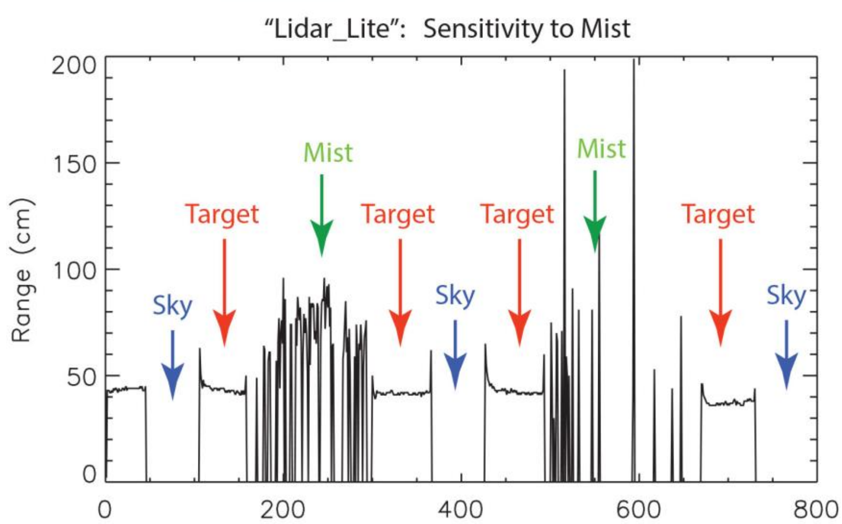


Figure 6: Demonstration of sensitivity of the "Lidar-Lite" lidar to mist within the viewing path of the instrument.

GliderSonde

The glidersonde is a small unmanned airplane designed to be deployed from a manned aircraft that can be guided during a slow gliding descent to sample vertical profiles with higher resolution than a dropsonde, and to enable lateral variations to be observed. The glider sonde caries the same differential IR flux sensor as the dropsondes. Data is telemetered at 10Hz to the deploying aircraft (for as long as it can loiter near the drop zone), but also stored on board for later uplink to the deploying aircraft (e.g. when it returns to the vicinity of the drop zone on the return leg of its Arctic Domain Awareness mission). The SmartSonde is a version of the GliderSonde with an electric motor and propeller, that can remain aloft longer, do climbing and descending vertical profiles, explore lateral variations more extensively, etc. Due to safety concerns from the Coast Guard, work to date has focused on the GliderSonde version. See Figure 7.

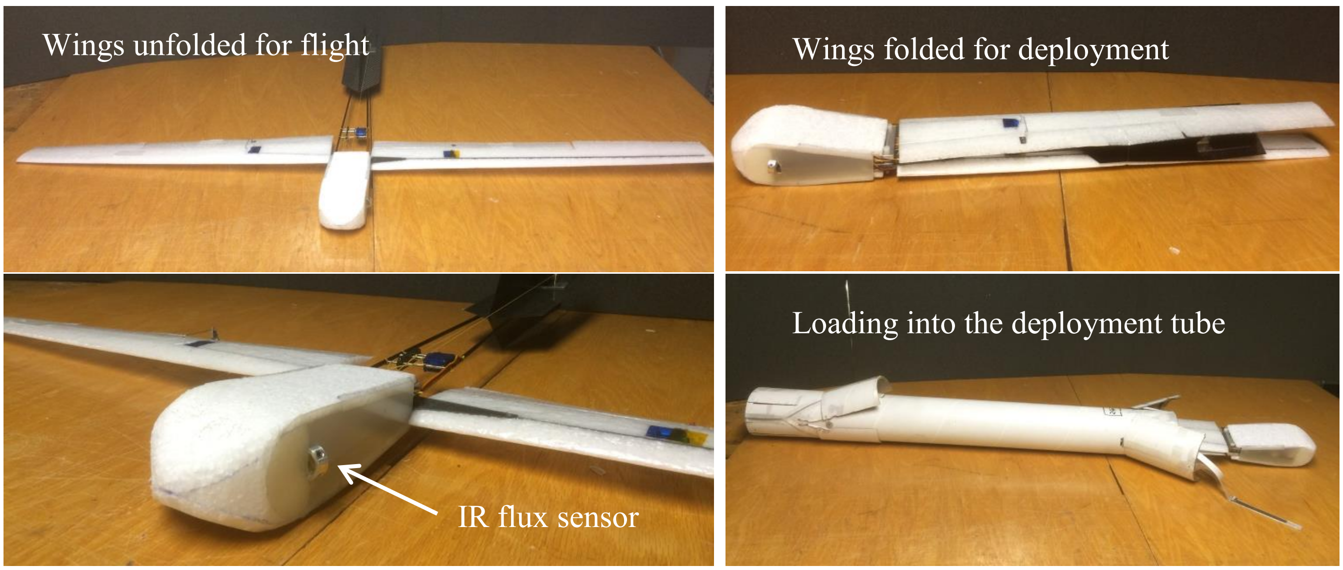


Figure 7: GliderSonde was designed to fit into a compact deployment tube during the shock of deceleration, then unfold wings for slow, long duration flight. It carries the same IR flux sensor as the IR dropsonde. The SmartSonde variant adds an electric motor and propeller on the tail.

Although several attempts were made to conduct a GliderSonde deployment from the Coast Guard C-130 as proposed, to date the Aviation Configuration Control Board has not yet approved the GliderSonde for this use. Although some informal positive indications have been forwarded by personnel at the Kodiak station, no details or time frames have been available. Nor have there been any problems or concerns raised. The Coast Guard SOFT test for electromagnetic compatibility with the C-130 for the Glidersonde and the associated laptop computer was successfully passed in May, 2015, with a 2-day ground test in Kodiak.

Instead, GliderSonde tests have been carried out by deploying from a Super Cub over the CU Boulder South flight range. This aircraft is much smaller, but can fly at 100 knots, which is just under the minimum airspeed of the C-130 at 120 knots. It is also much more convenient for initial testing. To date, we have conducted a series of 4 sorties over Boulder South, each dropping two GliderSondes in their individual protective tubes.

The Super Cub is a tandem two-seat aircraft, with a small cargo area behind the second seat (Figure 8). On each flight, two GliderSonde deployment tubes, each 36in long and 4in in diameter, were stowed in the cargo area, then prepared and hand-launched out the side door, in a similar way as planned for hand launch from the open rear ramp of the C-130. The deployment was supported by a tablet PC on the lap of the deployer in the second seat, running the same software planned for use on the C-130.

Figure 8: Super Cub aircraft deploying the GliderSonde in its deployment tube, launched by hand from the back seat out the size door. Photo captured by a Go-Pro camera mounted on the Super Cub wing tip.

The essential difficulty of GliderSonde deployment is the large speed disparity between the GliderSonde (airspeed of 20 knots) versus the deploying manned aircraft (about 100 knots). This requires a sequence of deployment steps to slow the protective tube down before the GliderSonde can be safely released. Analysis of these steps have been carried out using basic physics models, together with data on coefficients of drag for the deployment tube, drag fins, and parachute, obtained from a ground-based bungee launch apparatus (Figure 9). This resulted in the baseline design of the deployment tube (Figure 10) and the deployment sequence outlined below.

Figure 9: Initial testing for drag forces on the deployment tube, drag fins, and parachute, using a giant bungee launcher at the Boulder South flight range.

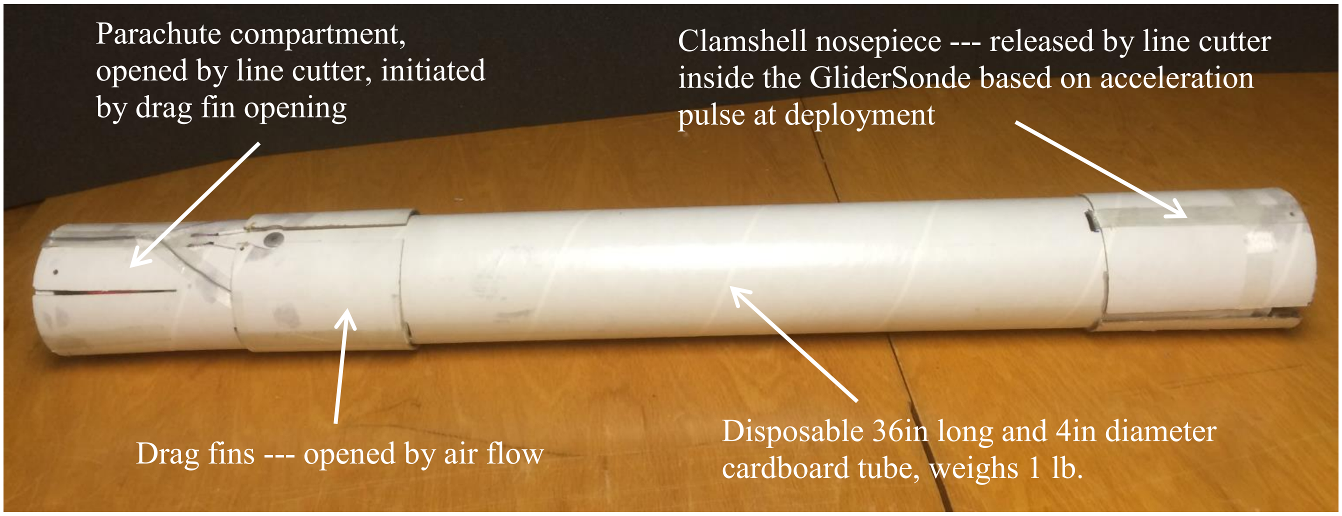


Figure 10: GliderSonde deployment tube, used to protect the GliderSonde and reduce airspeed for safe GliderSonde release.

GliderSonde Deployment Sequence

1. GliderSonde is powered inside the deployment tube by pressing a button on the nose of the GliderSonde that protrudes from an access port in the front of the deployment tube.

2. The control station computer is powered, and the MATLAB initialization application is launched. (Figure 11).

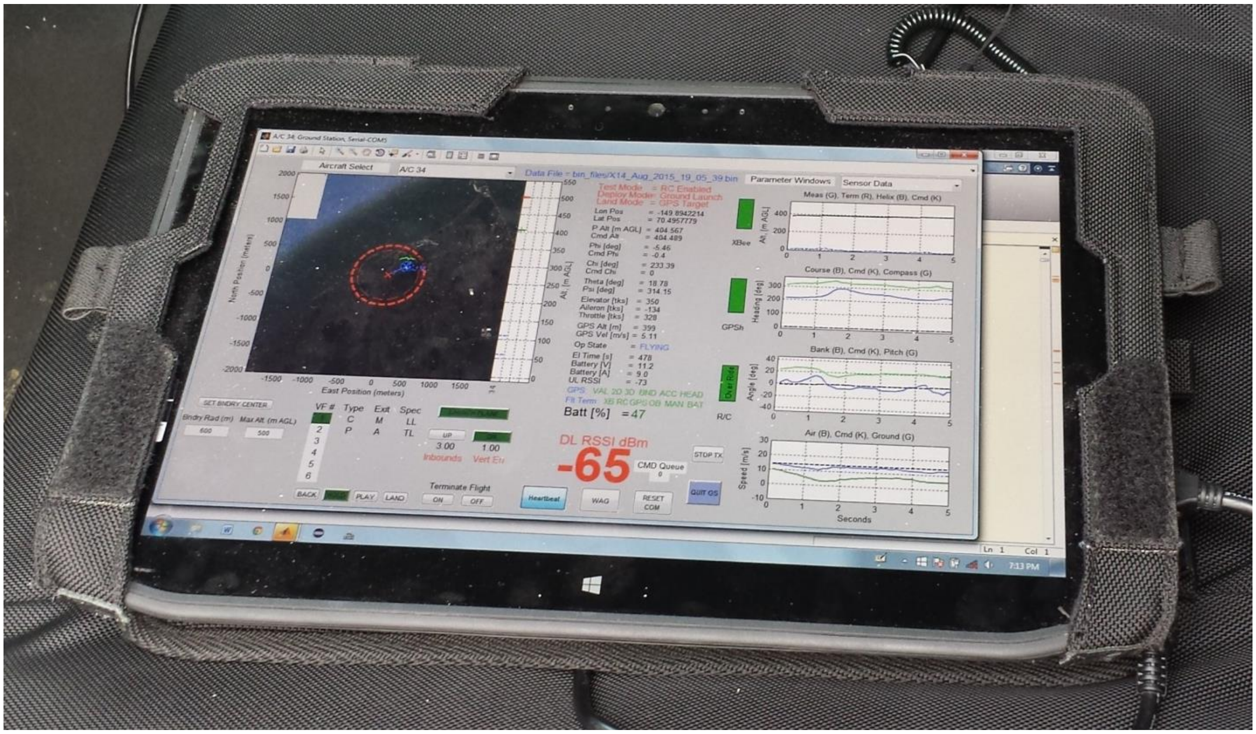


Figure 11: control station on a tablet PC, used to initialize the GliderSonde before deployment, and to monitor the subsequent flight.

3. The GliderSonde is initialized through the 900MHz data link to the control station computer, and telemetry data are checked for validity (e.g. valid GPS fix).

4. The GliderSonde is armed for release using buttons on the control station computer screen.

5. The parachute release circuit in the rear of the deployment tube is armed by connecting its integral battery.

6. A crew member deploys the GliderSonde tube by throwing it into the airstream with the aft end first, so that the nose will point into the relative wind. This sudden wind opens up two drag fins at the rear of the deployment tube to slow down the tube sufficiently so that the parachute will not be ripped away when it is suddenly inflated. Opening of these fins breaks an electrical contact, starting a timed process to cut a nylon line that releases the parachute from the aft end of the deployment tube about 2 seconds after the toss. (See Figure 12).

Figure 12: Deployment of the GliderSonde in its deployment tube, showing the drag fins opened at the rear, initiating the timed parachute release circuit, visible on the aft end of the tube. Photo captured by a Go-Pro camera mounted on the horizontal tail of the Super Cub.

7. The sudden deceleration of the GliderSonde in the deployment tube as it hits the airstream is detected by the autopilot in the GliderSonde, and this starts a deployment timer. After six seconds, the parachute has been deployed and the tube is hanging approximately vertically on the parachute at terminal descent velocity of about 6 m/s. (Figure 13).

8. The timer then enables another nylon line cutter to open the nose of the deployment tube and let the GliderSonde drop out of the tube, but it the GliderSonde remains tethered just below by another nylon line.

9. After 2 seconds to cut the first line and drop out, the GliderSonde wings are unfolded by a continuous rotation servo and locked in place by a spring-loaded detent mechanism. The flight control servos are also enabled at this time. See Figure 14.

Figure 13: Descending on the parachute, at 6m/s terminal velocity, slower than the GliderSonde airspeed of 10 m/s, enabling safe release from the tube.

10. After 6 seconds to unfold the wings, a third line cutter severs the connection to the tube and parachute, and the GliderSonde is free to fly away and follow its pre-programmed descent trajectory.

11. Measurements during the descent are stored on board in a SD card, and also telemetered to the computer control station for monitoring (at least as long as the deploying aircraft can loiter over the drop zone).

12. When the GliderSonde lands on the ocean surface, the recorded data are uplinked in two modes. The first sends current GPS position every second, to aid in locating the landed GliderSonde by the deploying aircraft as it returns on its inbound leg of the mission. The second mode replays the recorded data at a high rate every 5 minutes, so the control computer on the deploying aircraft can capture all of the data taken during the approximately 30 minute descent of the GliderSonde, once it has been located on the surface.

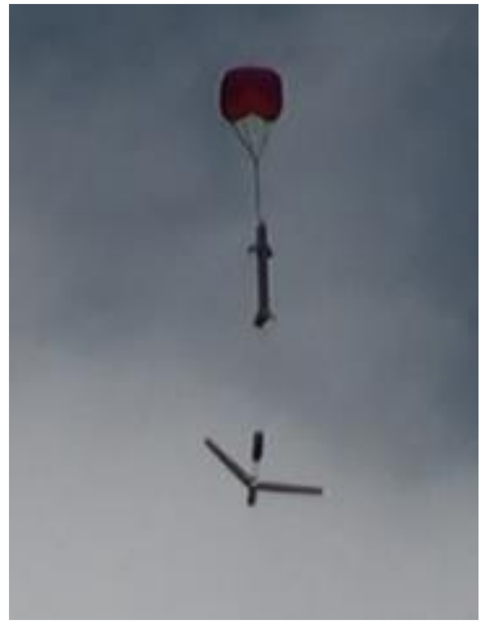


Figure 14: After GliderSonde has been ejected from the tube, its wings are unfolded while still tethered and descending slowly on the parachute.

IMPACT/APPLICATIONS

The vertical structure of the atmospheric profiles and cloud are regulated by the synoptic conditions. Using our *k*-mean classification algorithm, we are able to investigate the interactions between atmosphere, cloud, and the underlying sea ice under similar synoptic conditions. This approach allows us to focus on the different physical processes involved in these interactions. For example, under synoptic conditions S02, the weak stratification and wet conditions favor the cloud formation and maintenance. The cloud and radiative processes might be more important for the underlying sea ice. Under synoptic condition S04, the warm, dry, and strongly stratified atmosphere suppress the cloud formation. The associated stronger low level winds might be more important forcing for sea ice. In addition, evaluation of Polar-WRF simulations under different synoptic conditions will help to more clearly identify the deficiencies in the representation of these processes and identify the pathway to improve the weather and sea ice forecast in the BCSIZ region. New technology developments such as the IR flux and ranging sensors, IR dropsonde, GliderSonde and SmartSonde will provide opportunities to inexpensively obtain data that is otherwise not available (i.e. cloud base in remote locations, and cloud top and intermediate layers in any location) and allow more detailed data collection across the ice-edge. Our evaluation of sea ice drift forecasts skills provides a baseline from which improvements in the future can be measured. As a multi-year integrated observation and modeling study, SIZRS is well positioned to advance our predictive capabilities in the BCSIZ.

RELATED PROJECTS

Zhang (PI) MIZMAS: Modeling the Evolution of Ice Thickness and Floe Size Distributions in the Marginal Ice Zone of the Chukchi and Beaufort Sea (ONR, MIZ DRI)
Morison (PI) Ocean Profile Measurements During the SIZRS (ONR Core)
Steele (PI). UptempO buoys for understanding and prediction (ONR-Core)
Lindsay (PI). Visible and Thermal Images of Sea Ice and Open Water from the Coast Guard Arctic Domain Awareness Flights (ONR-Core)
Rigor (PI). International Arctic Buoy Program (ONR-Core)
Morison (PI). SIZRS Coordination (ONR-Core)
Tschudi (PI). CUPLIS-X (ONR-Core)
Overland (PI). (ONR-Core)

PUBLICATIONS

D. Lawrence and N. Curry, "SmartSonde: A low cost, aircraft-deployable UAS for atmospheric measurements in remote locations", in preparation for *Journal of Atmospheric and Oceanic Technology*.

D. Lawrence, J. Maslanik, and A. Schweiger, "Low cost IR flux sensor for in-situ cloud density and margin sensing", in preparation for *Atmospheric Measurement Techniques*.